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DEPARTMENT OF PHYSICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139
37-551

May 24, 1995

Ms. Angela Evan
NASA Goddard Space Flight Center
Code 286.1
Greenbelt, MD 20771

Final Technical Report
for **NASA Grant NAG5-1993**

Dear Ms. Evan:

During the period June 1992 through April 1994 we were supported in part by NASA grant **NAG5-1993** to carry out studies of possible chaotic behavior in the Rapid Burster X-ray source. First we obtained the 1985 EXOSAT data on the Rapid Burster that we had proposed to analyze. These data-trains consisted of four separate observations, ranging in duration from approximately 6 hours to 14 hours, and containing a total of about a thousand bursts. One data set, in particular, from 13 September, 1985, contained 219 consecutive bursts (i.e., with no data gaps). In addition, we also obtained HEAO A-1 data on the Rapid Burster, which contained several hundred bursts during a 3-hour observation interval.

The Rapid Burster data were analyzed by several different methods to determine whether there was evidence for chaotic behavior. The advantage of the EXOSAT data (with respect to other data sets, e.g., from HEAO A-1 and SAS-3) was that relatively long continuous data strings were possible because of the highly elliptical orbit of the satellite. Although some of the analysis we planned to perform could be done even with gaps in the data, frequent gaps can render some of the techniques less effective than they otherwise might be. Hence, the value of the EXOSAT data. Unfortunately it turned out that the gross behavior of the Rapid Burster was not the same during the different sets of observations we studied. (For example, the average time between bursts varied among the data sets.) This meant that, although data from individual satellite orbits provided reasonably long continuous data strings, data from some orbits had to be separated from data from other orbits, according to the two different modes of behavior observed. This diminished the potential effectiveness of some of the analyses we performed.

The methods of analysis we used were based largely on phase-space reconstruction techniques and included the following:

1. *Grassberger-Procaccia Analysis of Dimensionality* – In this case we considered several time series derived from the X-ray light curves. The first was an analysis of the intensity as a function of time. Since this was inconclusive in determining a low-dimensionality for the system, we proceeded to study the time series derived from the time interval between bursts. This analysis was also inconclusive with regard to determining a dimensionality for the system.

2. *Fourier Analysis* – There was no convincing evidence for the type of broad-band behavior that often characterizes the Fourier transforms of time series that emerge from chaotic systems.

3. *Lyapunov Analysis* – A comprehensive study was carried out as part of an undergraduate senior thesis by Marc Bockrath. That study demonstrated that, although one could derive Lyapunov exponents from the analysis, the values derived depended on the details of the way they were calculated. Specifically, Bockrath searched for regions in the parameter space where the results were stable. Although he was able to demonstrate the existence of such regions for

standard maps (e.g., Henon map), we were not able to do so for the Rapid Burster data.

4. *Forecasting-Based Analysis* – From the outset, we had thought that forecasting-based analyses were the most likely to bear fruit. As in the calculation of Lyapunov exponents, forecasting relies on studying the relative motion of points that start out close together in the reconstructed phase space, to determine whether such neighbors remain close. However, this approach seems to be more forgiving of gaps in the data and of short data trains.

After applying a forecasting technique (similar to that described by Sugihara & May 1990), we did not feel that we could say whether the data were chaotic or not. We therefore narrowed the goals of the investigation to ask "Is there a deterministic pattern in the time-ordering of the bursts?" Up to now, the "E-Δt" relationship between the energy in one burst and the time to the next burst was well known, but there is no known relationship among the various wait times between bursts. We therefore attempted to see if we could apply forecasting techniques to test the hypothesis that such a relationship existed. Although we did seem to derive a positive result, the result was sensitive to how the data set was divided up, even when considering data from just a single mode of behavior of the Rapid Burster. We therefore concluded that the result was not reliable. However, we plan to revisit this question.

In view of the somewhat promising results from the forecasting analysis, we applied a similar analysis to another important astrophysical data set, the light curve of the cataclysmic variable SS Cygni. Unfortunately, as with the attempts of others to learn whether that system exhibits chaos, our own attempts proved to be inconclusive.

In terms of practical outcomes, (1) an MIT undergraduate began participating in research on this project in the summer of 1992, and continued to work on this project, eventually writing his senior thesis on the search for chaos in the Rapid Burster. (2) We have published a paper in the proceedings of the Maryland Conference on X-Ray Binaries on this work: "A Search for Chaos in the Rapid Burster" by M. Bockrath, R. Di Stefano, & S. Rappaport (AIP Conference Proceedings 308, The *Evolution of X-Ray Binaries*, 1994, eds. S.S. Holt and C.S. Day, p. 543). A copy of this paper is enclosed. (3) We intend to pursue the work on forecasting somewhat further before closing the book on this investigation.

Summary – As with many other investigations of astrophysical data sets which set out to discover evidence of chaos, this investigation was inconclusive. Whereas a low signal-to-noise ratio has been the complicating factor for other investigations, it seems as if the primary difficulty here may have been that we simply needed more data (i.e., a longer train of bursts). Alternatively, it may be that there is no (reasonably) low-dimensional attractor for this system.

In addition to the above studies, the grant NAG5-1993 helped to support several theoretical studies related to X-ray binaries, including: "Production of Recycled Pulsars in Globular Clusters via Two-Body Tidal Capture" by R. Di Stefano, & S. Rappaport (ApJ, 1992, **396**, 587).

Sincerely,

Saul Rappaport

Saul Rappaport
Professor of Physics